Advanced numerical study of impact forces on railway sleepers under wheel flat

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Abstract
Wheel-rail interaction is one of the most important research topics in railway engineering. It includes track vibration, track impact response and safety of the track. Track structure failures caused by impact forces can lead to significant economic loss for track owners through damage to rails and to the sleepers beneath. The wheel-rail impact forces occur because of imperfections on the wheels or rails such as wheel flats, irregular wheel profile, rail corrugation and differences in the height of rails connected at a welded joint. In this paper, a finite element model for the wheel flat study is developed by use of the FEA software package ANSYS. The effect of the wheel flat to impact force on sleepers is investigated. It has found that the wheel flat significantly increases impact forces and maximum Von Mises stress, and also delays the peak position of dynamic variation for impact forces on both rail and sleeper.

Keywords: Wheel flat, Finite Element Analysis, Impact force, Concrete sleeper, ANSYS, Von Mises stress, Dynamic variation.

Introduction:
The wheel-rail impact forces occur because of imperfections in the wheels or rails such as wheel flats, irregular wheel profile, rail corrugation and differences in the height of rails connected at a welded joint. The values of impact forces can be so great and they can cause serious failure to the track structure.

In recent years, various researchers have focused on how to find the value of impact forces. A number of different simulation packages have appeared which are recorded in [7]. But those simulations were based on theoretical and traditional methods, thus the issues were solved with various assumptions. In this case, investigation of the impact forces on a sleeper derived from the wheel-rail forces is non-linear dynamic problem because the materials of track components are non-linear, and also impact process is a dynamic contact problem. The traditional impact analysis always assume the some bodies as rigid, and assume the flexible bodies as not large deformed, the contact methods based on Hertz theory are limited by the half-space assumption and the linear material model. The Finite Element Analysis (FEA) is not limited by those assumptions from traditional theoretical methods [3] and also because the some detailed analyses by classic dynamics equations are not feasible. Furthermore the experimental data is hard to obtain and it is usually only available for particular conditions of the track being tested.

In the past few years, a number of finite element models have been developed for analysing impact forces on railway track, such as a wheel-rail system for different heights at a rail joint [2] and a whole track structure model for heavy haul track [1]. Some wheel-rail forces have been simulated with FEA for research in wheel-rail contact interactions such as static-state and steady-state of rolling for predicting wear on wheel profile [3] [5]. The simulations mentioned above are all about wheels with perfect profile and which are either a linear dynamic analysis or a static analysis. A FE analysis of wheel-rail interaction was done with ANSYS by [6]; this model was used to test the maximum contact pressure to compare with traditional methods. They all have achieved the significant results. But no finite element model has been found for impact force analysis of non-linear railway track structures under wheel flats.

In this paper, based on ANSYS, a finite element model for the wheel flat study was developed. The effect of the wheel flat to impact force on sleepers was investigated. Importantly, the model can be used as a fundamental tool for more wide investigations in further research.

Finite Element Analysis

Because the wheel-rail dynamic interaction is a complicated problem and the components of wheel-rail system have complicated shapes, the analysis will only focus on the dynamic impact force, Von Mises stress and induced vibration on rail and sleeper based on a reasonable simplified model.

The complete model of the wheel-track system for this case includes a wheel, rail, three sleepers and ballast layer. All component models were created in Design Modeller of ANSYS Workbench. This system simulates the general passenger coach train described in [10], was used in the Manchester Benchmark described in [11]. According to the data recorded in [7], the speed of the benchmark vehicle was 160km/h, with standard track gauge and 685mm sleeper spacing. The rail was the UIC 60kg/m standard rail, and the sleepers were standard gauge concrete sleepers. All relevant vehicle parameters, track and sub track properties are available in [7].

The wheel is created by a simple cylinder with proper radius and thickness. The rail is created by extruding for a distance from a simple rectangle cross with same height as UIC60kg/m rail; the three sleepers are created by extruding the one rectangle cross section and arraying into three parallel objects according to the standard of concrete sleeper for standard gauge. Ballast layer is created by the shapes shown in diagram of track structure, which is shown in figure 1. Dimensions can be found in [7]. Because of the model is axial symmetric, the only a half of the entire track structure is considered.

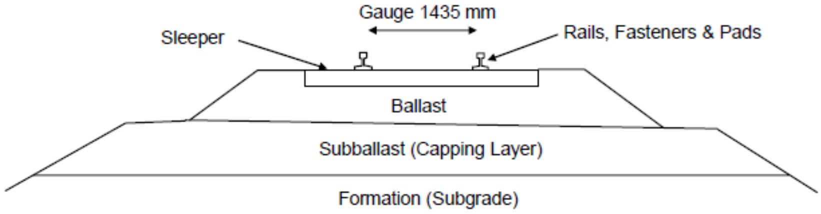

Figure 1 Diagram of railway track structure [7]

The material of wheel and rail can be defined as structural steel; the sleepers were defined as concrete, the ballast was defined as the material created by its properties found in [7]. The finished model is shown in figure 2.

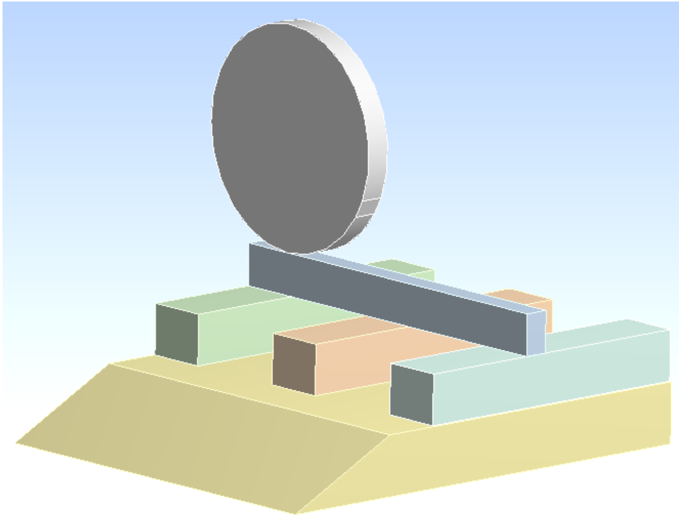

Figure 2 The wheel-track structure of simulation model

To analyse impact force caused by wheel-rail interaction under wheel flat situation, a flat surface with 80mm length was created on wheel and its location is presented in figure 3. This location can make the impact force caused by flat surface to be transformed from top of rail to the top of the tested sleeper.

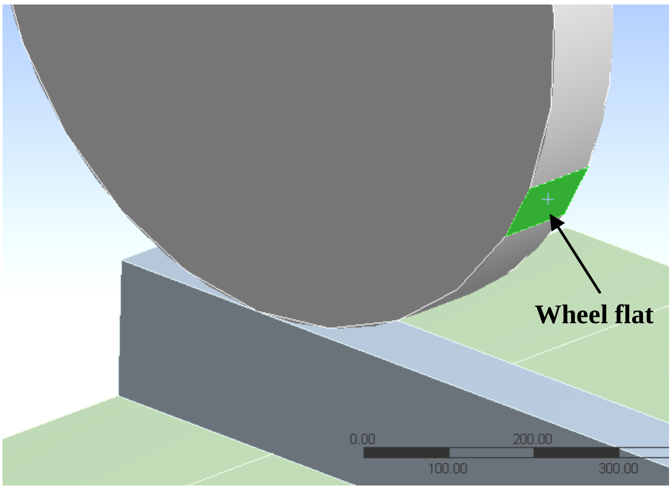

Figure 3 Location of the wheel flat surface

The entire model was meshed variously in different areas to ensure the result would be as precious as possible. In this model, the contact areas of wheel-rail and rail-sleeper are the stress concentrated areas. So, both were fine meshed; the rest of the areas on wheel, rail and sleepers were medium meshed; the ballast layer was coarse meshed. All components in this model were meshed by 3D finite-element meshes. The minimum finite-element meshes was 2.5mm in wheel flat area, impacted area of rail and the sleeper area below the impacted area of rail and the model consists of 87258 nodes and 71517 elements. The meshed model is presented in figure 4 a, and detail of fine meshed area is presented in figure 4 b.

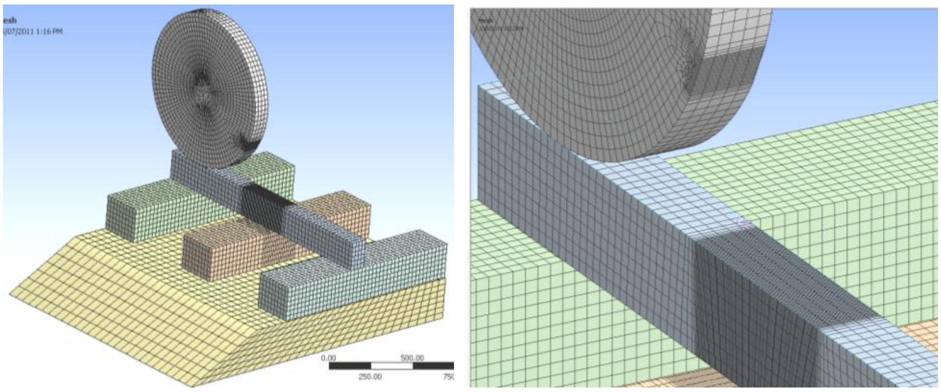

Figure 4 Completed meshing of models (a) the entire model; (b) detail of important contact area.

The applied conditions include defining types of contact areas, boundary conditions and applied loads. In this model, only the wheel is moving, other components contact with each other, thus, all of contacts between components in entire track structure are bonded. The contact area between profile of wheel and top of rail is also bonded to ensure wheel rolls on rail without sliding.

The applied load on this model is the force on wheel, and rotation speed is given. The force on wheel is the equivalent load converted from half of gross load of car body, bogie frame and wheel shaft. According to the parameters of Manchester vehicle in benchmark [7], the converted force is approximately 50kN. The running speed of the Manchester vehicle is 160km/h and converted to an angular velocity of the wheel is 96.62rad/s. Then, setup the expected solution options to run the model. For comparison, a perfect wheel case with same load and speed situation as flatted wheel case is also analysed.

Results and Discussions

The simulation results of Von Mises Stress and contact force on the rail are shown in figures 5 and 7 respectively. From these two figures, it is found that the flat profile impacts on part of rail above the analysed sleeper approximately at 0.0122s, so the greatest impact force should occur at that moment. The maximum Von Mises stress on top of rail as shown in figure 5 is 133MPa, and the impact force on rail as shown in figure 7 is 533kN.

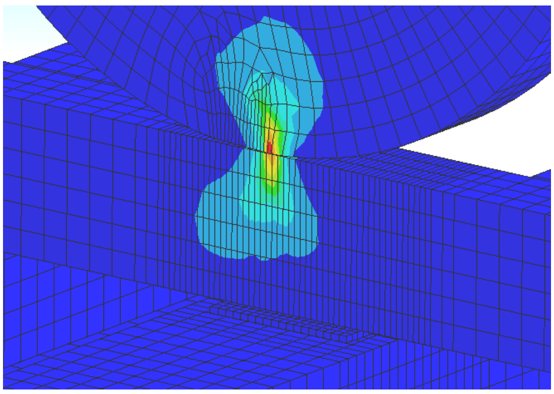

Figure 5 Simulation result of Von Mises stress at the time of flat profile impact

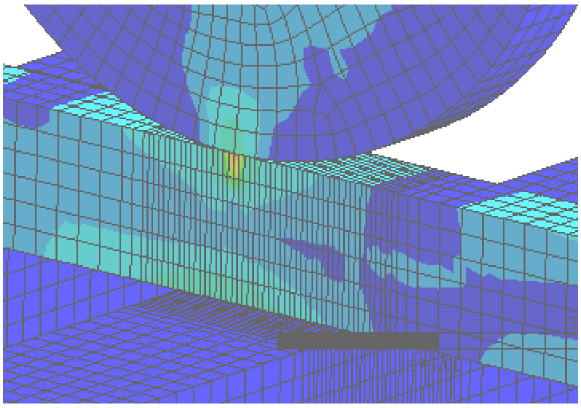

Figure 6 Simulation result of Von Mises stress with perfect wheel at the time of wheel on analysed sleeper

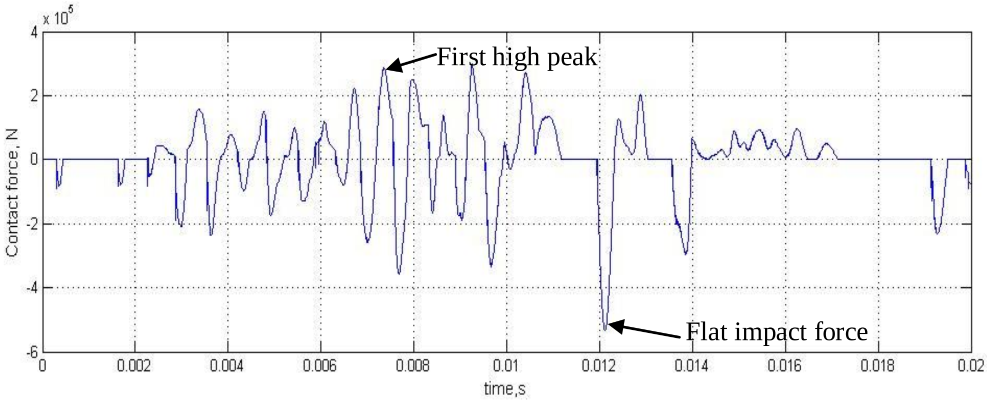

Figure 7 Contact force on rail caused by flatted wheel

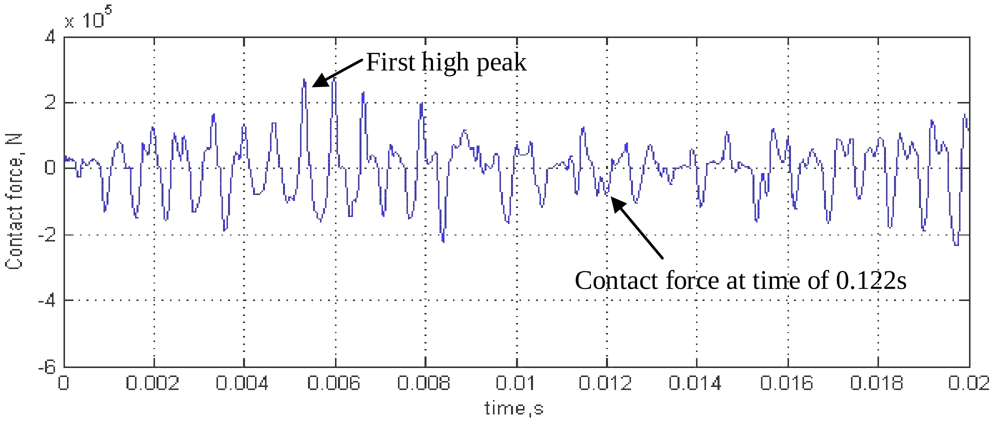

Figure 8 Contact force on rail caused by perfect wheel

For comparison, a perfect wheel case has been also simulated. This simulation also analysed the moment same as the flat profile impact moment which is approximately 0.0122s, to find out contact force under perfect profile wheel rolling. Setting the time at 0.0122s, we can see the simulation results of maximum Von Mises stress at time of 0.0122s as shown in figure 6 is 51MPa. The contact force on analysed sleeper at that moment is approximately 70kN as shown in figure 8.

From the above two simulation cases, we can conclude that a flatted wheel induces much larger maximum contact forces on rail than a perfect wheel. However, contact forces for these two cases have the similar shapes and frequencies of dynamic variation. The peak position of the dynamic variation for impact forces induced by flatted wheel is delayed to that induced by perfect wheel for nearly 0.002s indicated by the first high peak as shown in figures 7 and 8.

Because of the rail is on the top of sleepers and ballast is beneath, the contact forces on sleepers can be calculated by the resultant contact forces from both of rail and ballast.

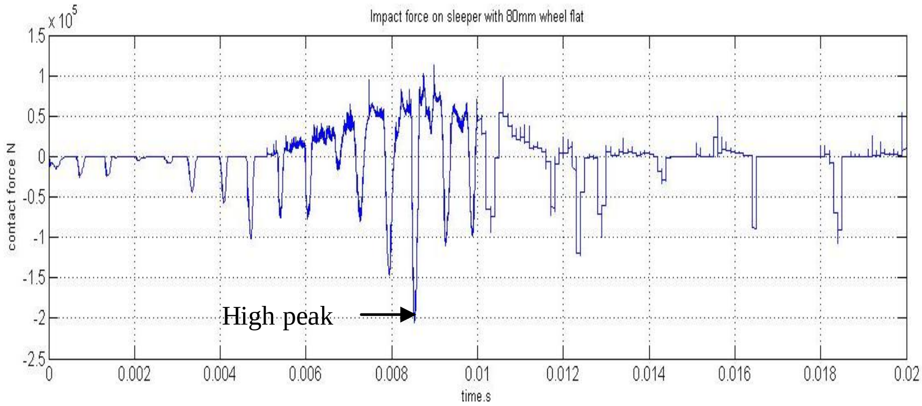

Figure 9 Contact force on analysed sleeper with flatted wheel

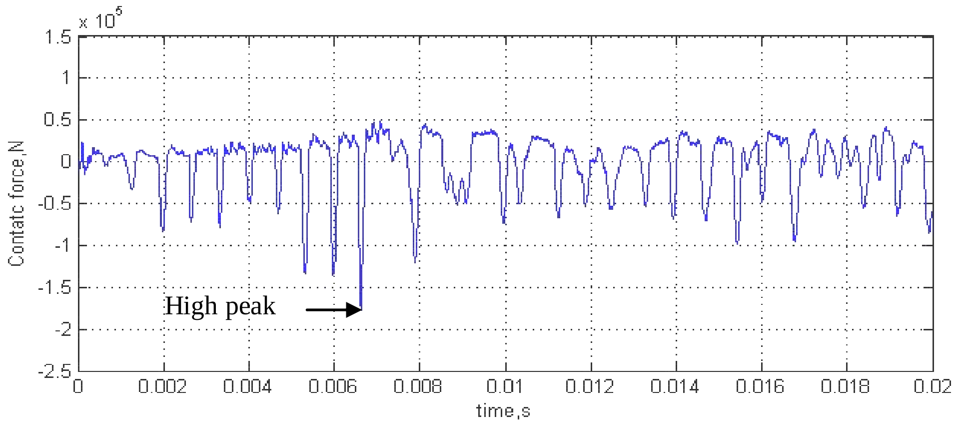

Figure 10 Contact force on analysed sleeper with perfect wheel

Figures 9 and 10 show dynamic sleeper contact forces caused by the flatted wheel and the perfect wheel, respectively. At the moment of 0.0122s shown in figure 9, the value of contact force on sleeper closes to 0, but the contact force on rail is 533kN (as shown in Figure 7). It means the ballast provides a counter contact force, approximate 533kN, on sleeper. Because the effective contact areas with rail and ballast are different, the sleeper is under largest bending moment. As shown in figure 10, the sleeper contact force at this moment also closes to 0 and rail contact force is approximately 70kN (as shown in figure 8). The peak position of the dynamic variation for impact forces induced by flatted wheel is also delayed to that induced by perfect wheel for nearly 0.002s indicated by the high peak as shown in figures 9 and 10.

Conclusion

The Finite Element models for impact force, which are included by flatted wheel and perfect wheel, on sleeper have been developed. The results have shown that the difference in maximum Von Mises stress and impact forces induced by flatted wheel and perfect wheel on both rail and tested sleeper. The vibration phases of both rail and tested sleeper are also affected. The presented numerical results indicate that flatted wheel induces much larger impact force and Von Mises stress than a perfect wheel; the peak positions of the dynamic variation for impact forces induced by flatted wheel delays to that induced by perfect wheel.

The flat on the wheel is an important factor that must be considered in analysis of the wheel-rail interaction system.

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